OFF-CYCLE LIGHT-DUTY DIESEL VEHICLE EMISSIONS UNDER REAL-WORLD DRIVING CONDITIONS

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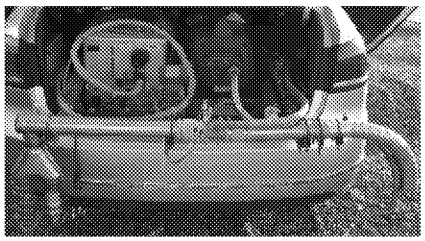

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  - CO_2 emissions and fuel economy
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BACKGROUND AND MOTIVATION

- Increased ***off-cycle NO_x emissions*** identified from light-duty diesel vehicles in Europe
  - exceed the Euro 3-5 emissions standards on average by a factor of 4 to 7 over specific test routes
- Vehicles meet certification levels for emissions while operated over standard chassis dynamometer cycles (e.g. FTP-75, NEDC)
  - introduction of tighter emissions limits for the purpose of vehicle certification has not necessarily translated into effective on-road NO_x reductions of the same magnitude
  - NO_2 levels in European member states exceeding ambient air quality standards
  - Exhaust temperature dependency of SCR activity (low load operation, stop/go traffic)
- European Commission established working group to propose modifications to current vehicle certification procedure
  - emissions testing with random driving cycle generation in the laboratory
  - on-road emissions testing with PEMS equipment

=> Need to characterize off-cycle NO_x emissions from Tier2-Bin5 / LEV-II ULEV light-duty diesel vehicles operating in US

Weiss, M., Bonnel, P., Hummel, R., Manfredi, U., Colombo, R., Lanappe, G., Le Lijour, P., and Sculati, M., "Analyzing on-road emissions of light-duty vehicles with Portable Emission Measurement Systems (PEMS)," JRC Scientific and Technical Reports, EUR 24627 EN, (2011).

METHODOLOGY - Test Vehicles

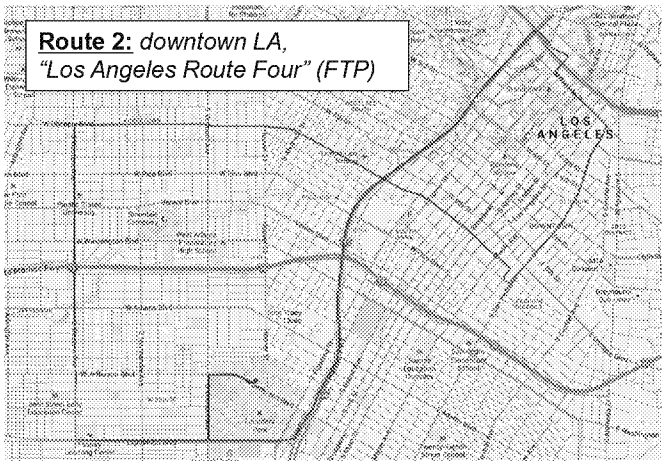
Vehicle		A	B	C
Mileage at test start [miles]		4,710	15,226	15,031
Fuel		ULSD	ULSD	ULSD
Engine displacement [L]		2.0	2.0	3.0
Emission after-treatment technology		**OC, DPF, LNT**	**OC, DPF, urea-SCR**	**OC, DPF, urea-SCR**
Drive train		2-wheel drive, front	2-wheel drive, front	4-wheel drive
Applicable emissions limit	*U.S. EPA*	**Tier2 - Bin5 (LDV)**	**Tier2 - Bin5 (LDV)**	**Tier2 - Bin5 (LDV)**
	CARB	**LEV-II, ULEV**	**LEV-II, ULEV**	**LEV-II, LEV**
EPA Fuel Economy Values [mpg] [1]	*City*	29	30	19
	Highway	39	40	26
	Combined	33	34	22
EPA CO_2 Values [g/km] [1]		193	186	288
Actual Test Weight [kg]		1855	1884	2903
Payload [kg]		305	314	533

[1] *EPA advertised fuel economy and CO_2 emissions values for new vehicles in the US (www.fueleconomy.gov)*

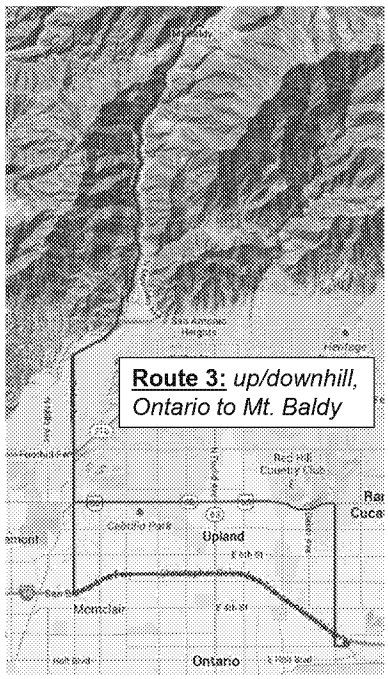
- Vehicles did not indicate any after-treatment or engine malfunction (ECU scan)
- *Vehicles A* and *B* were tested on chassis dynamometer and complied with certification standards for all regulated emissions

METHODOLOGY - Test Routes

- Route 1: *highway driving in Los Angeles*
- Route 2: *urban driving in downtown Los Angeles*
- Route 3: *rural and uphill/downhill driving in LA's foothills*
- Route 4: *urban driving in downtown San Diego*
- Route 5: *urban driving in downtown San Francisco*



Route 2: *downtown LA, "Los Angeles Route Four" (FTP)*



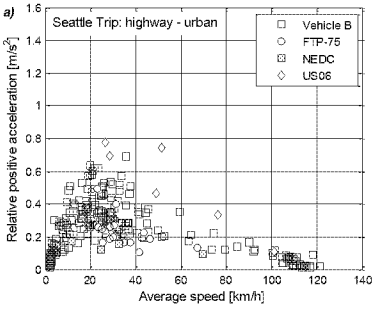
Route 3: *up/downhill, Ontario to Mt. Baldy*

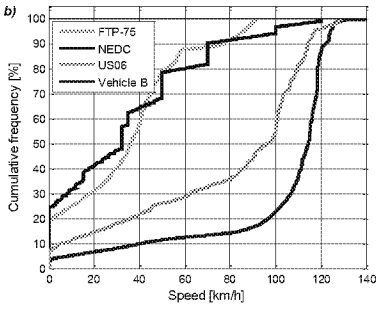
METHODOLOGY - 'Multi-State' Route

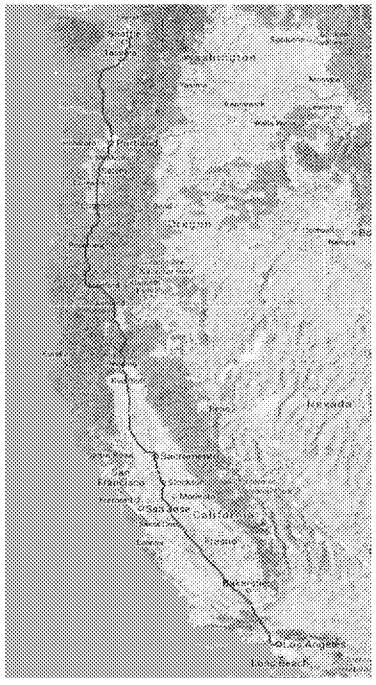
- Los Angeles to Seattle via Interstate I-5N and I-5S

Parameters	Value
Route duration [hr]	39.31
Route distance [km]	3968.10
Avg. vehicle speed [km/h]	100.95
Max. vehicle speed [km/h]	120.00
Avg. RPA [1] [m/s²]	0.23
Characteristic Power [m²/s³]	2.63
Min. elevation [m a.s.l. [2]]	1.0
Max. elevation [m a.s.l.]	1320.1

Parameters	Value
Share [%] (*time based*)	
- idling (≤2 km/h)	3.4
- low speed (>2≤50 km/h)	8.1
- medium speed (>50≤90 km/h)	5.0
- high speed (>90 km/h)	83.5

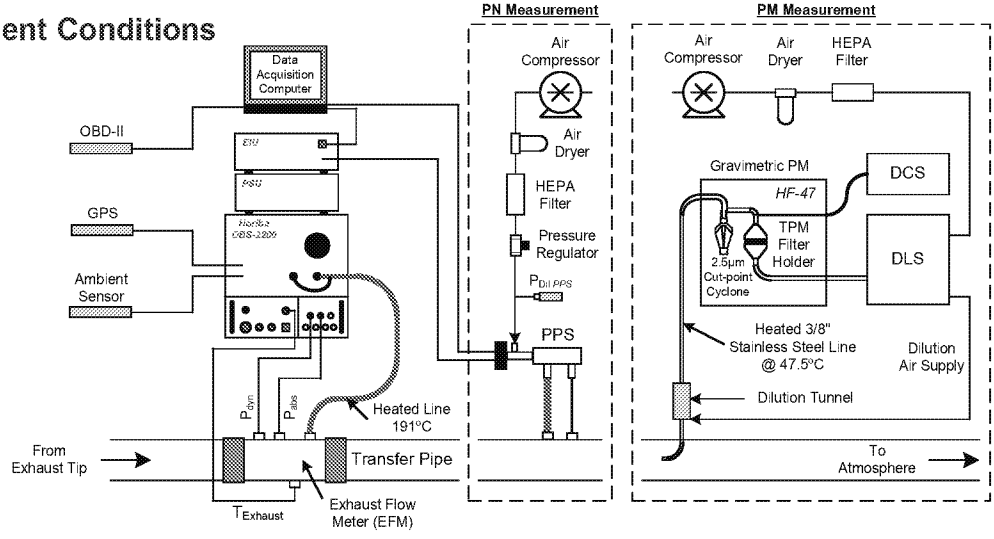






METHODOLOGY - Instrumentation

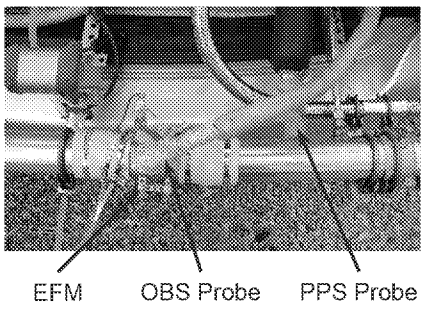
- **Gaseous Emissions:** Horiba OBS-2200 PEMS
- **PM Emissions:** Pegasor Particle Sensor (PPS-M) and Horiba OBS-TRPM
- **ECU OBD-II Data**
- **Ambient Conditions**
- **GPS**



METHODOLOGY - Test Matrix

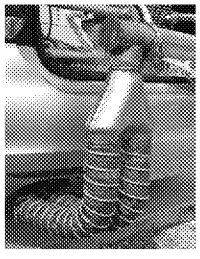
- On-road vehicle test matrix

Route	Vehicle A	Vehicle B	Vehicle C
Route 1: highway	2	2	1
Route 2: urban (Los Angeles)	2	2	2
Route 3: rural - uphill/downhill	2	2	3
Route 4: urban (San Diego)	2	2	
Route 5: urban (San Francisco)		1	2
Cross-State Trip CA to WA		X	



- Emissions measurement matrix

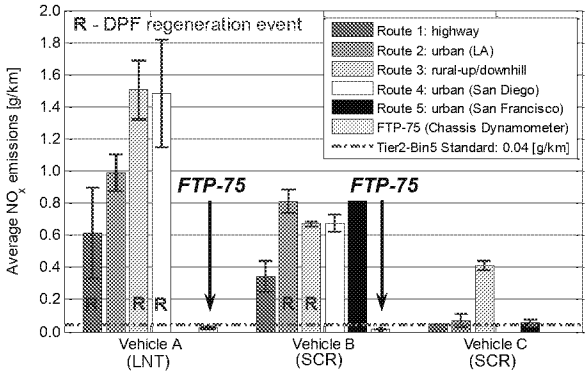
Component	Vehicle A	Vehicle B	Vehicle C
Gaseous emissions	X	X	X
Particle number (*PPS*)	X	X	
Particle mass (*OBS-TRPM*)			X



- Instrumentation readiness during 'multi-state' route

Instrument	Total time of operation [hr]	Fraction of total trip duration [%]	Total distance of operation [km]	Fraction of total trip distance [%]
OBS (gaseous emissions)	23.6	60.1	2352.0	59.3
ECU (engine parameter)	31.2	79.4	3143.3	79.2
PPS (particle emissions)	22.7	57.8	2304.6	58.1

RESULTS - Routes NO_x Emissions

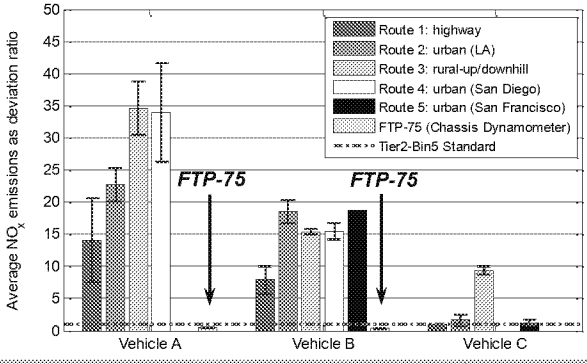


- Highest NO_x emissions during rural/up-downhill and lowest NO_x during highway driving
- LNT shows deficiencies in NO_x reduction over urea-SCR system
- Increase in NO_x emissions during tests with DPF regeneration event => especially pronounced for *Vehicle A* (LNT)
- Route 1, Vehicle A contains rush-hour and non-rush-hour traffic conditions

Chassis dynamometer test results for NO_x

Vehicle	NO_x over FTP-75 [g/km]	Rel. to Tier2-Bin5 [%]
Vehicle A	0.022 ±0.006	50.4
Vehicle B	0.016 ±0.002	64.1
Vehicle C	(no data)	(no data)

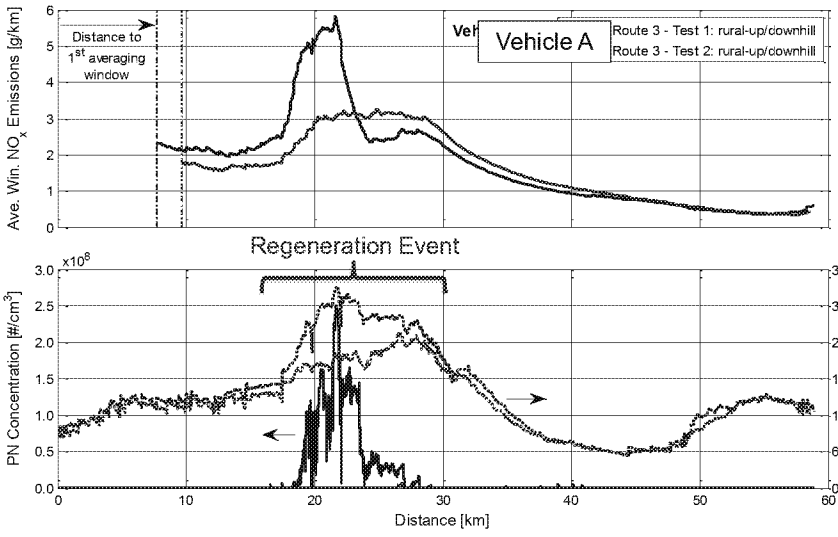
NO_x standard EPA Tier2-Bin5, CARB LEV-II ULEV over FTP-75: ***0.044 g/km***



24th CRC Real World Emissions Workshop
March 26-29, Newport, 2014
San Diego, California

RESULTS - Routes NO_x Emissions

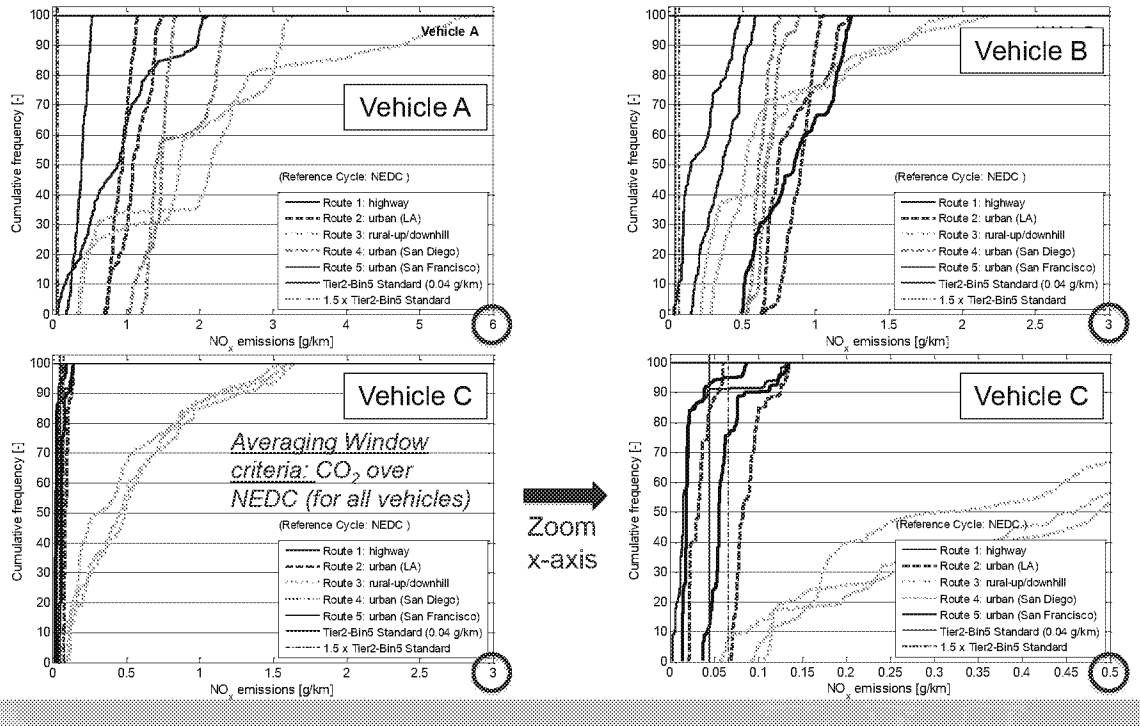
- Comparison of tests with and without DPF regeneration for Vehicle A, Route 3 (up/downhill)
  - Continuous averaging window NO_x emissions vs. distance
  - Particle number concentrations and exhaust gas temperatures (at exhaust tip) vs. distance



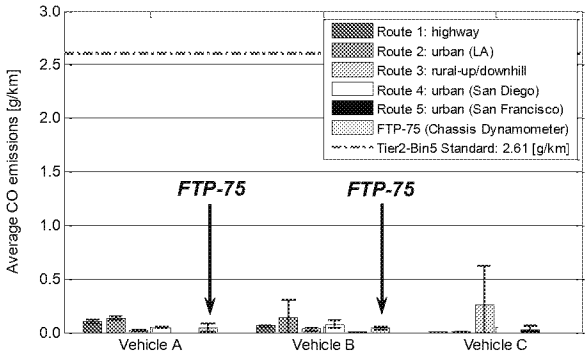
Averaging Window criteria:
CO_2 emissions over NEDC (1938.6g)

4th CRC Real World Emissions Workshop
March 30th, Austin, 2016
San Diego, California

RESULTS - Averaging Window NO_x Emissions



RESULTS - Routes CO/THC Emissions

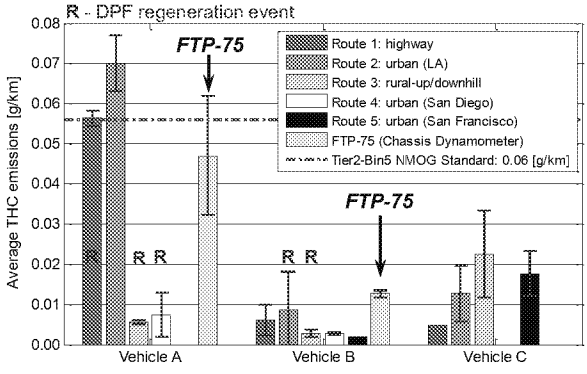


- THC emissions in general below NMOG (NMHC) Tier2-Bin5 standard
- **Caution:** Chassis dynamometer testing showed >80% CH_4/THC ratio
  - Only THC measured during on-road testing

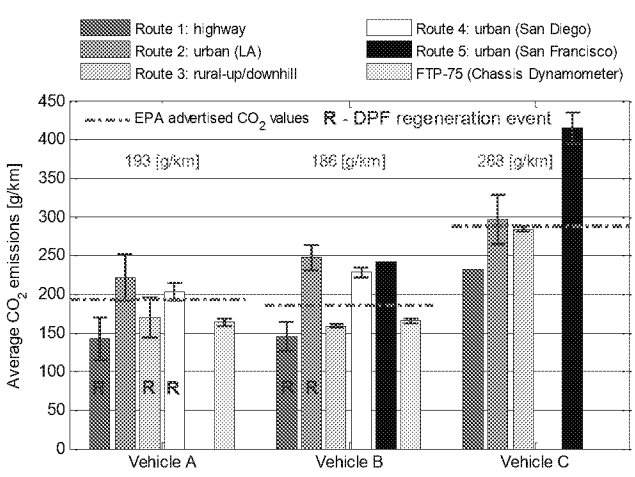
Chassis dynamometer testing over FTP-75

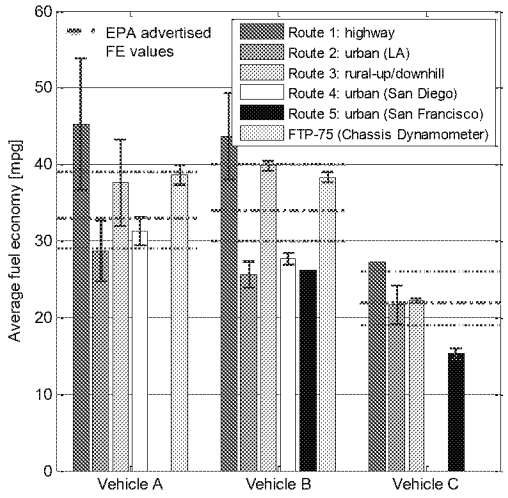
	Vehicle A	Vehicle B
CH4/THC Ratio [%]	99.87	87.23

- CO emissions close to two orders of magnitude below Us-EPA Tier2-Bin5 standard
- No particular pattern found for CO as function of driving or route conditions
- *Vehicles A* and *C* show highest CO during urban and highway driving



RESULTS - Routes CO_2 Emissions

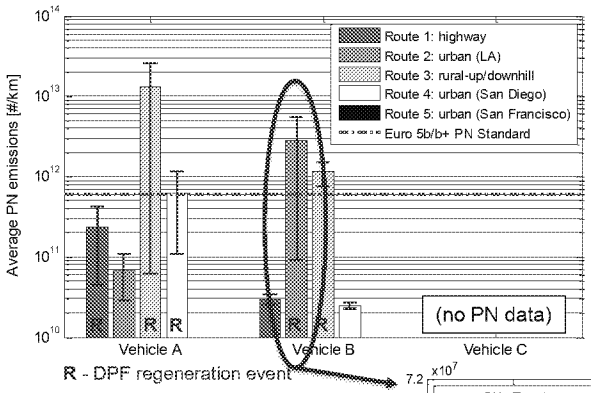




- Highway driving (i.e. Route 1) showed lowest CO_2 emissions / best fuel economy
- Urban/suburban driving showed highest CO_2 emissions / lowest fuel economy
- A 31% increase in CO_2 observed between non-rush-hour and rush-hour highway driving for *Vehicle A*
- Increased CO_2 emissions observed during DPF regeneration events for *Vehicles A* and *B*

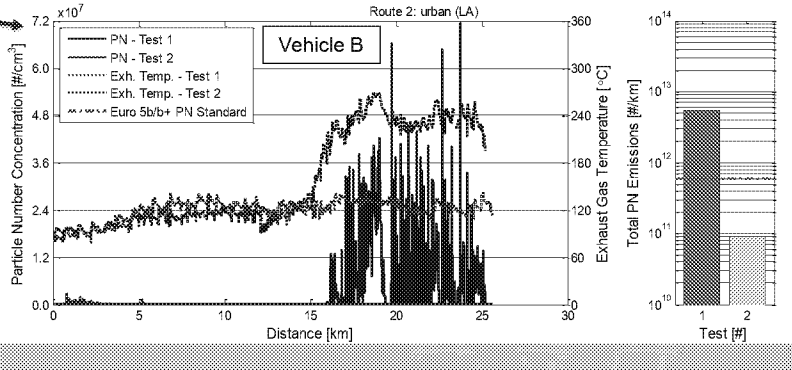
4th CRC Real World Emissions Workshop
March 30 - April 02, 2014
San Diego, California

RESULTS - Routes PN Emissions

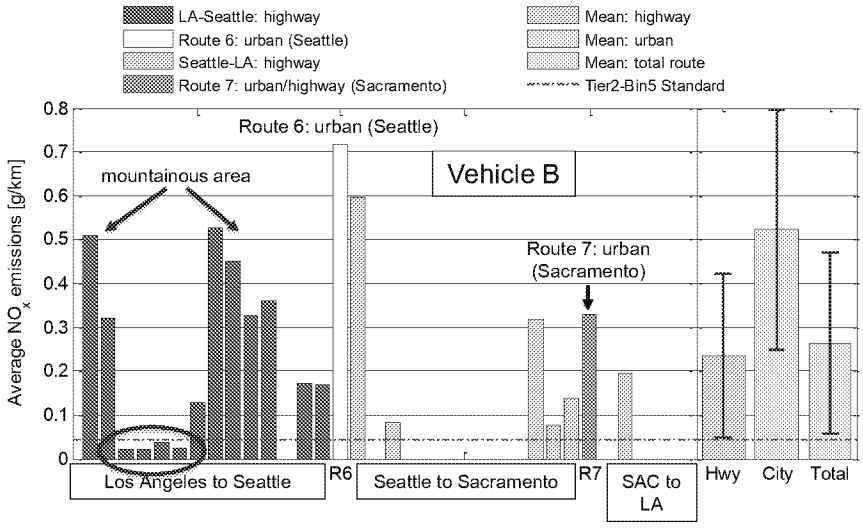


- Euro 5b/b+ standard: 6×10^{11} [#/km]
- **Caution:** PN inferred from PPS measurements => sampling conditioning and particle counting not strictly according to PMP method
- PN increased by up to two orders of magnitude during DPF regeneration events

- In general PN remain one order of magnitude below Euro 5b/b+ standard for tests without DPF regeneration events

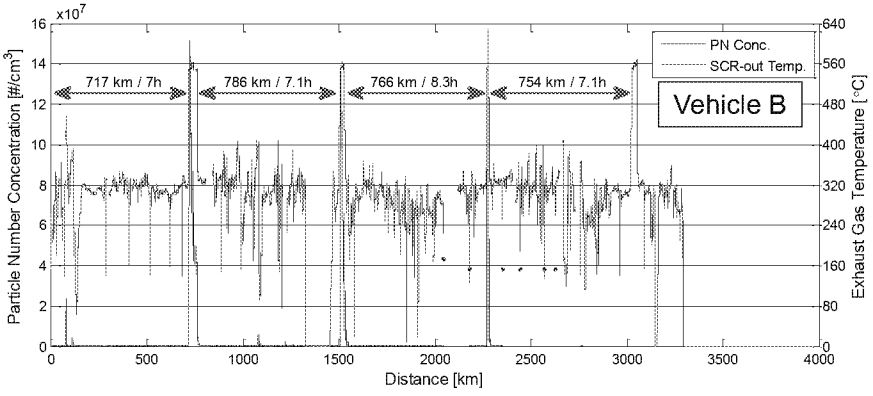


RESULTS - 'Multi-State' Route NO_x



- Exceeding NO_x Tier2-Bin5 standard on average by a factor of 6 over entire route
- NO_x emissions below Tier2-Bin5 level observed during traveling northbound on I-5 through San Joaquin Valley
  - low or negligible changes in altitude (i.e. near zero road grade)
  - Vehicle operated at constant speed conditions of 120km/h (cruise-control mode)

RESULTS - 'Multi-State' Route PN



- Distance and time based DPF regeneration intervals for Vehicle B (*primarily highway*)
  - Avg. distance: 756km ±29km (±1σ)
  - Avg. time: ~7.07hours ±0.06hours (±1σ, not including third event)

Event [#]	Distance to event [km]	Distance based f_{regen} [km]	Time to event [hr]	Time based f_{regen} [hr]	Duration [min]
1	717	*717*	7.0	*7.0*	22.4
2	1,503	*786*	14.1	*7.1*	15.2
3	2,269	*766*	22.3	*8.3*	7.5
4	3,023	*754*	29.5	*7.1*	15.8

CONCLUSIONS

- *Vehicles A* and *B* complied with regulatory standards for all pollutants during chassis dynamometer testing over certification cycles (*Vehicle C* was not tested).
- In-use NO_x emissions
  - *Vehicle A*: 15-35 times higher than the FTP standard,
  - *Vehicle B*: 5-18 times higher than FTP standards,
  - *Vehicle C*: generally below the FTP standard.
- DPF regeneration events were observed to increase NO_x emissions by up to 50% for the LNT equipped vehicle (only small effect on SCR vehicles observed)
- In-use HC emissions were far below the standard for *Vehicles B* and *C* and slightly higher but remaining below the standard for *Vehicle A*.
- In-use CO emissions were far below the standard for all three vehicles.
- In-use PN emissions were generally one order of magnitude below $6x10^{11}$ [#/km] during routes that did not experience DPF regeneration events.
- PN emissions increased by up to two orders of magnitude during DPF regeneration events

RECOMMENDATIONS / OUTLOOK

- Limited sample space (three vehicles, two technologies, only one sample per vehicle) does not allow to draw definitive implications/conclusions.
  - Increased sample numbers required => additional testing of more vehicles needed
- Large discrepancy observed between NO_x emissions from certification testing on chassis dynamometer an on-road testing needs further investigation.
  - Might SFTP (incl. US06 cycle) NO_x standards be too lenient, allowing for increased NO_x emissions under higher load conditions?
- *Vehicle C* has shown that NO_x emissions at the Tier2-Bin5 standard during diverse on-road operation is possible.
- More study needed for very high NO_x emissions observed during particulate filter regeneration events, especially for LNT system
- More work needed to understand PN emissions => PMP method versus capturing below 23nm partilces

THANK YOU FOR YOUR ATTENTION

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CAFEE Center for Alternative Fuels, Engines and Emissions

ACKNOWLEDGEMENT

icct THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

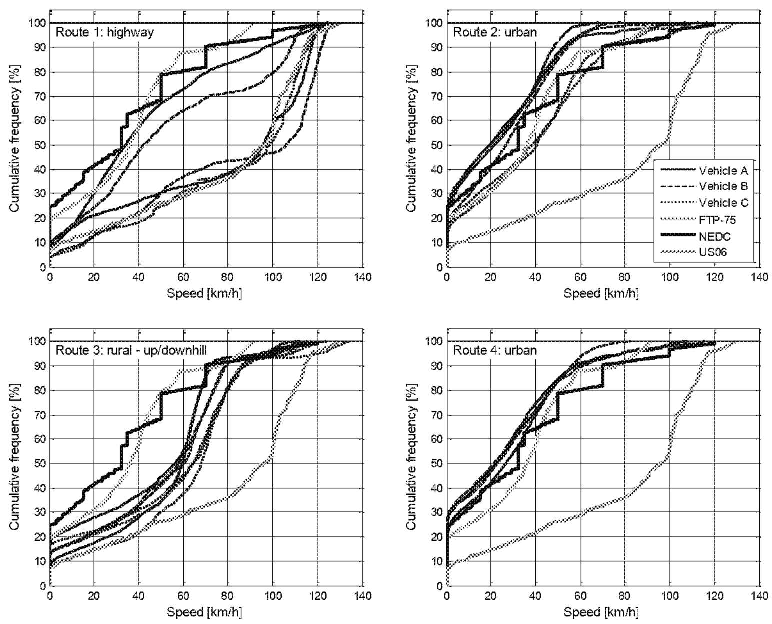
AIR RESOURCES BOARD

METHODOLOGY - Test Routes

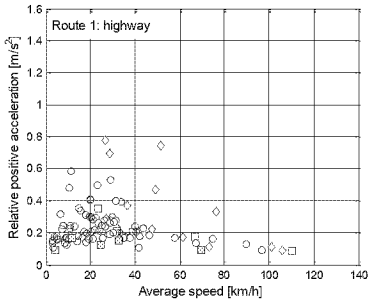
- Route 1: *highway driving in Los Angeles*
- Route 2: *urban driving in downtown Los Angeles*
- Route 3: *rural and uphill/downhill driving in Los Angeles's foothills*
- Route 4: *urban driving in downtown San Diego*
- Route 5: *urban driving in downtown San Francisco*

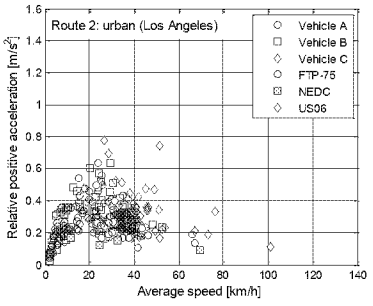
Route	Route 1	Route 2	Route 3	Route 4	Route 5
Route distance [km]	70.18	25.67	59.09	21.22	26.72
Avg. vehicle speed [km/h]	77.85	24.09	52.27	26.54	24.69
Max. vehicle speed [km/h]	112.65	92.57	112.65	109.87	112.65
Avg. RPA [3] [m/s²]	0.24	0.27	0.26	0.30	0.33
Characteristic Power [m²/s³]	2.57	2.24	3.93	2.60	2.97
Min. elevation [m a.s.l. [4]]	46.0	42.1	300.1	1.1	1.0
Max. elevation [m a.s.l]	360.1	123.5	1319.7	101.4	190.9
Share [%] (*time based*)					
- idling (≤2 km/h)	7.0	23.8	13.5	26.8	27.9
- low speed (>2≤50 km/h)	20.5	64.2	23.9	57.0	58.9
- medium speed (>50≤90 km/h)	14.9	11.2	55.6	12.9	7.5
- high speed (>90 km/h)	57.7	0.8	7.0	3.3	5.6

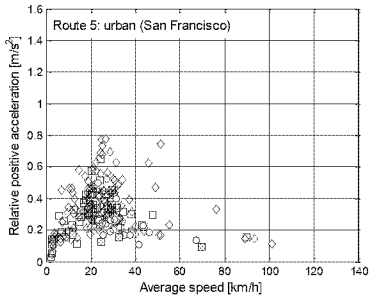
METHODOLOGY - Test Routes

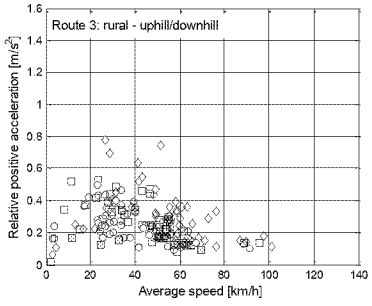


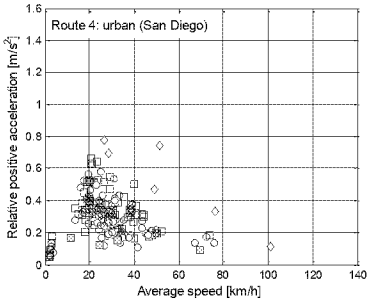
METHODOLOGY - Test Routes











Relative Positive Acceleration

- RPA over given "*micro-trip*"
- *"Micro-trip"*
  - Speed > 2km/h for t ≥ 5sec

$$\mathrm{RPA} = \frac{\int_0^{t_j} (v_i \cdot a_i) dt}{x_j}$$

RESULTS - Data Analysis

- Applicable regulatory emissions limits; US-EPA Tier2-Bin5 at intermediate useful life (5years/ 50,000 mi) for NO_x, CO, THC (eq. to NMOG), and PM; EPA advertised CO_2 values for each vehicle; Euro 5b/b+ for PN

NO_x [g/km]	CO [g/km]	THC [g/km]	CO_2 [g/km]	PM [g/km]	PN [#/km]
0.043	2.610	0.056	193 (*Vehicle A*) 186 (*Vehicle B*) 288 (*Vehicle C*)	0.006	6.0×10^{11}

- Window size criterion for AWM; total CO_2 mass over FTP-75 and NEDC (evaluated at CARB El Monte chassis dynamometer laboratory for Vehicle A and B; taken from EPA certification document for Vehicle C)

Vehicle	CO_2 over FTP-75 [g]	CO_2 over NEDC [g]
Vehicle A	2921.9	1938.6
Vehicle B	2944.8	1841.8
Vehicle C	5042.5	5042.5 [1)]